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13. ABSTRACT (Maximum 200 words) Humans demonstrate a remarkable ability to regulate daily body water and electrolyte balance so long as food and fluid are readily available. The imposition of exercise and environmental stress can, however, challenge this ability. Most circumstances involving physical exercise require the formation and vaporization of sweat as the principle means of heat removal in man. Sweat losses, if not replaced, reduce body water volume and electrolyte content. Excessive body water or electrolyte losses can disrupt physiological homeostasis and threaten both health and performance. Persons often dehydrate during physical activity or exposure to hot weather because of fluid non-availability or a mismatch between thirst and body water losses. In these instances, the person begins the task with normal total body water and dehydrates over a prolonged period. This scenario is common for most athletic and occupational settings, however, in some situations the person might begin exercise with a body water deficit. For example, in several sports (e.g., boxing, power lifting, wrestling) athletes frequently dehydrate to compete in lower weight classes. Also, persons medicated with diuretics may be dehydrated prior to initiating exercise. If sodium chloride deficits occur then the extracellular fluid volume will contract and cause "salt depletion dehydration." A sodium chloride deficit usually occurs due to sweat sodium losses combined with excessive water consumption, but a sodium deficit can also occur without excessive water intake owing to high sweat sodium losses. Both of these scenarios produce sodium dilution more commonly known as hyponatremia or "water intoxication". This chapter reviews the physiology, needs, and assessment of human water and electrolyte balance. The extent to which water and electrolyte imbalances affect temperature regulation and exercise performance are also considered. Throughout the chapter, euhydration refers to normal body water content, hypohydration refers to a body water deficit, and hyperhydration refers to increased body water content. Dehydration refers to the dynamic loss of body water.			
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33

Human Water and Electrolyte Balance

Scott J. Montain, Samuel N. Cheuvront,
Robert Carter, III, Michael N. Sawka

Introduction

Humans demonstrate a remarkable ability to regulate daily body water and electrolyte balance so long as food and fluid are readily available.¹ The imposition of exercise and environmental stress can, however, challenge this ability. Most circumstances involving physical exercise require the formation and vaporization of sweat as the principle means of heat removal in man. Sweat losses, if not replaced, reduce body water volume and electrolyte content. Excessive body water or electrolyte losses can disrupt physiological homeostasis and threaten both health and performance.¹

Persons often dehydrate during physical activity or exposure to hot weather because of fluid non-availability or because of a mismatch between thirst and body water losses.² In these instances, the person begins the task with normal total body water, and dehydrates over a prolonged period. This scenario is common for most athletic and occupational settings; however, in some situations the person might begin exercise with a body water deficit. For example, in several sports (e.g., boxing, power lifting, wrestling) athletes frequently dehydrate to compete in lower weight classes. Also, persons medicated with diuretics may be dehydrated prior to initiating exercise. If sodium chloride deficits occur, then the extracellular fluid volume will contract and cause “salt depletion dehydration.” A sodium chloride deficit usually occurs due to sweat sodium losses combined with excessive water consumption, but a sodium deficit can also occur without excessive water intake owing to high sweat sodium losses. Both of these scenarios produce sodium dilution, which is more commonly known as hyponatremia or “water intoxication.”^{3,4}

This chapter reviews the physiology, needs, and assessment of human water and electrolyte balance. The extent to which water and electrolyte imbalances affect temperature regulation and exercise performance are also considered. Throughout the chapter, the term euhydration refers to normal body water content, hypohydration refers to a body water deficit, and hyperhydration refers to increased body water content. Dehydration refers to the dynamic loss of body water.

Physiology of Water and Electrolyte Balance

Net body water balance (loss = gain) is generally regulated well as a result of thirst and hunger drives coupled with free access to food and beverage.¹ This is accomplished by neuroendocrine and renal responses⁵ to body water volume and tonicity changes, as well as non-regulatory social-behavioral factors.⁶ These homeostatic responses collectively ensure that small degrees of over- and underhydration are readily compensated for in the short term. Using water balance studies, Adolph^{7,8} found that daily body water varied narrowly between 0.22% and 0.48% in temperate and warm environments, respectively. However, exercise and environmental insult often pose a greater acute challenge to fluid balance homeostasis.

Water (total body water) is the principal chemical constituent of the human body. For an average young adult male, total body water is relatively constant and represents 50% to 70% of body weight.⁹ Variability in total body water is primarily due to differences in body composition.^{1,9} Total body water is distributed into intracellular fluid (ICF) and extracellular fluid (ECF) compartments. The ICF and ECF contain about 65% and 35% of total

body water, respectively. The ECF is further divided into the interstitial and plasma spaces. Water balance represents the net difference between water intake and loss. When losses exceed intakes, total body water is decreased.

When body water deficits occur from sweat losses, a hypertonic hypovolemia generally results. Plasma volume decreases and plasma osmotic pressure increases in proportion to the decrease in total body water. Plasma volume decreases because it provides the fluid for sweat, and osmolality increases because sweat is ordinarily hypotonic relative to plasma. Resting plasma osmolality increases in a linear manner from about 283 mosmol/kg when euhydrated, to more than 300 mosmol/kg when hypohydrated by 15% of total body water.¹ The increase in osmotic pressure is primarily due to increased plasma sodium and chloride, with no consistent effect on potassium concentrations.¹⁰⁻¹²

Incomplete fluid replacement decreases total body water, and as a consequence of free fluid exchange, affects each fluid space.¹³⁻¹⁶ For example, Nose et al.¹⁵ determined the distribution of body water loss among fluid spaces as well as among different body organs during hypohydration. They thermally dehydrated rats by 10% of body weight, and after the animals regained their normal core temperature, the body water measurements were obtained. The fluid deficit was apportioned between the intracellular (41%) and extracellular (59%) spaces. Regarding organ fluid loss, 40% came from muscle, 30% from skin, 14% from viscera, and 14% from bone. Neither the brain nor liver lost significant water content. They concluded that hypohydration results in water redistribution largely from the intra- and extracellular spaces of muscle and skin in order to maintain blood volume.

Different methods of dehydration are known or suspected to affect the partitioning of body water losses differently than those just described. For example, diuretics increase urine formation and generally result in the loss of both solutes and water. Diuretic-induced hypohydration generally results in an iso-osmotic hypovolemia, with a much greater ratio of plasma loss to body water loss than either exercise or heat-induced hypohydration.^{10,17} As a result, relatively less intracellular fluid is lost after diuretic administration, since there is not an extracellular solute excess to stimulate redistribution of body water. In contrast, several studies^{13,18,19} report substantial decreases in skeletal muscle intracellular water content following prolonged exercise without fluid replacement, presumably the result of water released with the breakdown of muscle glycogen. Exercise-induced hypohydration may therefore result in a greater intracellular water loss than simple sweat-induced hypohydration (passive thermal dehydration). Kozlowski and Saltin²⁰ reported data to support this view, but Costill and Saltin¹⁸ found no difference between exercise and thermal dehydration for the partitioning of water between the fluid compartments. It is therefore clear that the ratio of intracellular to extracellular water losses that occur with dehydration from sweating

and diuretic use are different, but any difference between active and passive sweating remains unresolved. Other factors such as heat acclimatization status, posture, climate, mode, and intensity of exercise can also produce significant variability in the responses described above.^{21,22}

Water and Electrolyte Needs

Human water and electrolyte needs should not be based on a “minimal” intake, as this might eventually lead to a deficit and possible adverse performance and health consequences. Instead, the Food and Nutrition Board of the Institute of Medicine bases water needs on Adequate Intake (AI). The AI is based on experimentally derived intake levels that are expected to meet nutritional adequacy for essentially all members of a healthy population. The AI level for water is 2.7 to 3.7 L/d for sedentary women and men over age 19, respectively.¹ These values represent total water intake from all fluids (80%) and foods (20%). The AI for sodium is 1.5 g/d or 3.8 g/d sodium chloride.¹ The report also indicates that athletes and workers performing stressful exercise in the heat can exceed the AI for water and sodium.

Table 1²³ illustrates the wide variability in hourly sweat losses observed both within and between sports and occupations. Depending upon the duration of activity and heat stress exposure, the impact of these elevated hourly sweat rates on daily water requirements will vary. **Figure 1** depicts generalized modeling approximations for daily water requirements based upon calculated sweating rates as a function of daily energy expenditure (activity level) and air temperature.¹ Applying this prediction model, it is clear that daily water requirements can increase two- to six-fold from baseline by simple manipulation of either variable. For example, daily water requirements for any given energy expenditure in temperate climates (20°C) can triple in very hot weather (40°C). In addition to air temperature, other environmental factors also modify sweat losses; these include relative humidity, air motion, solar load, and choice of clothing for protection against

Table 1. Sweating Rates for Different Sports (Data are from Rehrer N, Burke L. Sweat losses during various sports. Aust J Nutr Diet. 1996;53: S13–S16.)

Sport	Mean	Range
	L/h	
Water polo	0.55	0.30–0.80
Cycling	0.80	0.29–1.25
Running	1.10	0.54–1.83
Basketball	1.11	0.70–1.60
Soccer	1.17	0.70–2.10

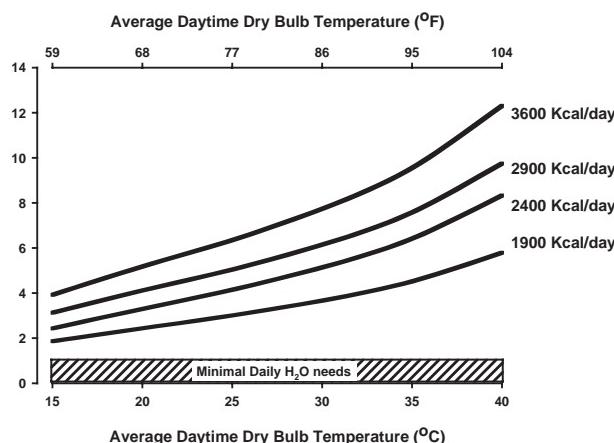


Figure 1. Daily water needs estimated from sweat loss predictions due to changes in physical activity and air temperature. Daily energy expenditures of 1900, 2400, 2900 and 3600 kcal correspond to sedentary, low activity, active, and very active, respectively. (From Food and Nutrition Board, Institute of Medicine. Dietary Reference Intakes for Water, Potassium, Sodium, Chloride, and Sulfate. Washington, DC: National Academies Press; 2004. Available online at: <http://www.nap.edu/books/0309091691/html>.)

environmental elements.²⁴ Therefore, it is expected that water losses, and therefore water needs, will vary considerably among moderately active people based on changing extraneous influences.

Sweat is hypotonic to extracellular fluid, but contains electrolytes, primarily sodium chloride and, to a lesser extent, potassium, calcium, and magnesium.²⁵⁻²⁷ Sweat sodium concentration averages 35 mEq/L (range 10–70 mEq /L) and varies depending upon diet, sweating rate, hydration level, and heat acclimation state.^{25,28,29} Sweat potassium concentration averages 5 mEq/L (range 3–15 mEq /L), calcium 1 mEq/L (range 0.3–2 mEq/L), magnesium 0.8 mEq /L (range 0.2–1.5 mEq/L), and chloride 30 mEq/L (range 5–60 mEq/L).²⁹ Neither gender nor aging seem to have marked effects on sweat electrolyte concentrations.^{30,31} Sweat glands reabsorb sodium by active transport, but the ability to reabsorb sweat sodium does not increase proportionally with the sweating rate. As a result, the concentration of sweat sodium increases at high sweating rates.^{25,28} Heat acclimation improves the ability to reabsorb sodium, so heat-acclimated persons have lower sweat sodium concentrations (>50% reduction) for any given sweating rate.²⁸

Figure 2 depicts generalized modeling approximations for daily sodium needs based upon calculated sweating rates as a function of daily energy expenditure (activity level) and air temperature.¹ This analysis assumes that persons are heat acclimated and have a sweat sodium concentration of 25 mEq/L (about 0.6 g/L). The average American diet contains about 4 g/d of sodium,¹ but this varies greatly depending upon ethnic preferences for food. Increases or decreases in sodium stores are usually corrected by adjustments in a person's salt appetite. In addition, when physical activity increases, the additional caloric intake associated with increased activity usually

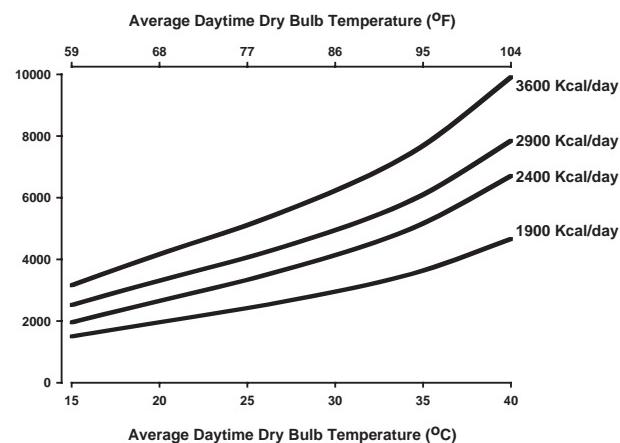


Figure 2. Daily sodium needs estimated from sweat loss predictions due to changes in physical activity and air temperature. Daily energy expenditures of 1900, 2400, 2900, and 3600 kcal correspond to sedentary, low activity, active, and very active, respectively. (From Food and Nutrition Board, Institute of Medicine. Dietary Reference Intakes for Water, Potassium, Sodium, Chloride, and Sulfate. Washington, DC: National Academies Press; 2004. Available online at: <http://www.nap.edu/books/0309091691/html>.)

covers the additional sodium required.¹ Therefore, sodium supplementation is generally not necessary (unless subjects are performing very heavy activity) for the first several days of heat exposure, as normal dietary sodium intake appears adequate to compensate for sweat sodium losses.^{2,32} If persons need additional sodium, this can be achieved by salting their food to taste. Another strategy is to rehydrate with fluids containing about 20 mEq/L of sodium. Most commercial sports beverages approximate this concentration.^{2,32}

Hydration Assessment

Although plasma osmolality is the criterion used as the hydration assessment measure for large-scale fluid needs assessment surveys,¹ the optimal choice of method for assessing hydration, particularly in sport, is limited by the circumstances and intent of the measurement. Popular hydration assessment techniques vary greatly in their applicability to laboratory or field use due to methodological limitations, which include the necessary circumstances for accurate measurement, ease of application, and sensitivity for detecting small, but meaningful changes in hydration status.³³

Although there is presently no consensus for using one assessment approach over another, in most athletic arenas, the use of first morning body mass measurements in combination with some measure of urine concentration should allow ample sensitivity (low false negative) for detecting deviations in fluid balance. When more precision of acute hydration changes is desired, plasma osmolality and isotope dilution provide for gradations in measurement.³³ However, the simplest way to track acute hydration changes is to measure body mass before and after exercise using the reasonable assumption that 1 g of lost

Table 2. Hydration Assessment Indices

Measure	Practicality	Validity (Acute vs. Chronic)	Euhydration Cutoff
Total body water	Low	Acute and chronic	< 2%
Plasma osmolality	Medium	Acute and chronic	< 290 mOsmol
Urine specific gravity	High	Chronic	< 1.020 g/ml
Urine osmolality	High	Chronic	< 700 mOsmol
Urine color	High	Chronic	< 4
Body mass	High	Acute and chronic*	< 1%

* Potentially confounded by changes in body composition during very prolonged assessment periods.

mass is equivalent to 1 mL of lost fluid. In fact, if proper controls are made, body mass changes can provide a more sensitive estimate of acute total body water changes than repeat measurements by dilution methods.³⁴ For longer periods (1–2-weeks), body mass may even remain stable enough to be a reliable hydration measure during periods of hard exercise and acute fluid flux whether in temperate^{35,36} or hot³⁷ climates. Table 2 provides definable thresholds from the literature,^{1,37–43} which can be used as a guide to detect a negative body fluid balance. Fluid intakes should be considered adequate when any two assessment outcomes are consistent with euhydration.

Fluid Balance, Temperature Regulation, and Exercise Performance

The difficulty encountered when trying to match fluid consumption to sweat losses during exercise can produce hypohydration by 2% to 6% of body weight.⁴⁴ Although this is more common in hot environments, similar losses are observed in cold climates when working in heavy clothing.⁴⁵ The mismatch between intakes and losses is due to physiological and behavioral factors.

Hypohydration

Hypohydration increases core temperature responses during exercise in temperate and hot climates.⁴⁶ In fact, a deficit of only 1% of body weight elevates core temperature during exercise.⁴⁷ As the magnitude of water deficit increases, the magnitude of core temperature elevation ranges from 0.1 to 0.23°C for every percent body weight lost,^{1,46} but the core temperature elevation may be greater during exercise in hot compared with temperate climates.⁴⁸ In addition, altering the time of fluid ingestion (early or late into the exercise bout) does not modify the core temperature elevation from progressive dehydration.⁴⁹ Hypohydration not only elevates core temperature, but also negates the core temperature advantages conferred by high aerobic fitness and heat acclimation.⁴⁶

When hypohydrated, elevated core temperature responses result from a reduction in the capacity for heat dissipation. The relative contributions of evaporative and

dry heat loss during exercise depend upon the specific environmental conditions,⁵⁰ but both avenues of heat loss are adversely affected by hypohydration.¹ Local sweating and skin blood flow responses are both reduced for a given core temperature,^{46,48} and whole-body sweating is usually either reduced⁵¹ or unchanged⁵² during exercise at a given metabolic rate in the heat. However, even when hypohydration is associated with no change in whole-body sweating rate, core temperature is usually elevated, so that whole-body sweating rate for a given core temperature is lower. Both the singular and combined effects of plasma hyperosmolality and hypovolemia have been suggested as mediating the reduced heat loss response during exercise-heat stress.⁴⁸ Figure 3 summarizes the relative contributions of hyperosmolality and hypovolemia to adverse thermoregulatory responses during exercise in temperate and hot climates.⁴⁸ These effects are noticeably smaller in cooler environments.^{48,53,54}

Hypohydration can decrease dynamic exercise performance.¹ Dehydration by more than 2% of body weight degrades endurance exercise, especially in hot environments.^{1,55} The magnitude of the performance decrement is variable, and probably depends on the individual, on environmental conditions, and on exercise mode differences. However, for a given person and event, the greater the dehydration level (after achieving the threshold for performance degradation) the greater the performance

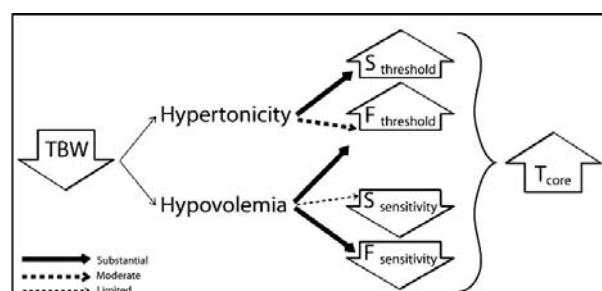


Figure 3. Effects of reducing total body water (TBW) on sweating (S) and skin blood flow (F) thresholds and sensitivities. Substantial, moderate, and limited descriptors are based on amount of supporting data. (From Cheuvront SN, Carter III R, Montain SJ, et al. Influence of hydration and airflow on thermoregulatory control in the heat. *J Therm Biol.* 2004;29:471–477.)

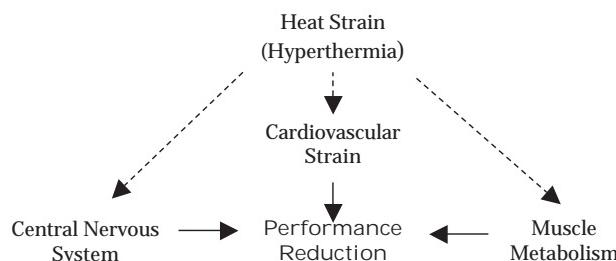


Figure 4. Physiologic factors that contribute to dehydration-mediated performance decrements. (From Cheuvront SN, Carter III R, Sawka MN. Fluid balance and endurance exercise performance. *Curr Sports Med Rep*. 2003;2:202–208.)

decrement. Dehydration probably does not alter muscle strength,⁵⁶ but sometimes has been reported to reduce dynamic small muscle endurance.^{57,58} In addition, dehydration of over 2% often adversely influences cognitive function in the heat; however, this area requires more research.¹

Physiologic factors that contribute to dehydration-mediated performance decrements include hyperthermia,^{59,60} increased cardiovascular strain,^{61,62} altered metabolic function,⁶³ or perhaps via events originating in the central nervous system^{55,58} (Figure 4). Though each factor is unique, evidence suggests that they interact to contribute in concert, rather than in isolation, to degrading exercise performance. The relative contribution of each factor may differ depending on the event, environmental conditions, and athletic prowess, but elevated hyperthermia probably acts to accentuate the performance decrement.^{55,64,65}

Hyperhydration

Hyperhydration is not easy to sustain, since overdrinking of water or carbohydrate-electrolyte solutions produce a fluid overload that is rapidly excreted by the kidneys.⁶⁶ Greater fluid retention can be achieved with an aqueous solution containing glycerol,^{66,67} which increases fluid retention by reducing free water clearance.⁶⁶ However, both exercise and heat stress decrease renal blood flow and free water clearance and therefore negate glycerol's effectiveness as a hyperhydrating agent if ingested during exercise.⁶⁸ Studies demonstrate that total body water can be increased by approximately 1.5 L and sustained for several hours with glycerol hyperhydration^{66,68}; however, glycerol provides no cardiovascular or thermoregulatory advantages over water ingestion alone when taken during exercise or heat stress.^{68–70} The effects of glycerol hyperhydration on performance are mixed. Glycerol hyperhydration may^{71–73} or may not^{69,70} improve exercise performance. Comparing study outcomes is complicated by differences in performance measures, climate, and the potentially confounding study design limitations.⁶⁸

Hyponatremia

Symptomatic hyponatremia (typically associated with serum sodium concentrations of less than 125–130 mEq/

L) has been observed during marathon and ultramarathon competition,^{74–76} military training,^{77,78} and recreational activities.⁷⁹ In athletic events, the condition is more likely to occur in females and slower competitors. The severity of the symptomatology is related to the magnitude that the serum sodium concentration falls and the rapidity with which it develops.⁸⁰ If hyponatremia develops over many hours, it might cause less brain swelling and fewer adverse symptoms.⁸⁰ The hyponatremia associated with prolonged exercise develops primarily because individuals drink excessively large quantities of hypotonic fluids (relative to sweating rate) for many hours.^{3,76,77} Unreplaced sodium losses contribute to the rate and magnitude of sodium dilution. Additionally, nausea (which increases vasopressin levels) and heat/exercise stress (which reduce renal blood flow and urine output) can negatively affect the ability of the kidney to rapidly correct the fluid-electrolyte imbalance.⁸¹ The syndrome can be prevented by not drinking in excess of the sweating rate, and by consuming salt-containing fluids or foods when participating in exercise events that produce multiple hours of continuous or near-continuous sweating.

Summary

Among the greatest challenges to body water homeostasis is exercise and environmental stress. Sweating results in water and electrolyte losses. Because sweat output often exceeds water intake, there is an acute water deficit that results in a hypertonic hypovolemia and intracellular and extracellular fluid contraction. Although water and electrolyte needs increase as a result of exercise, eloquent physiological and behavioral adaptations allow humans to regulate daily body water and electrolyte balance so long as food and fluid are readily available. Although there is presently no consensus for choosing one hydration assessment approach over another, deviations in daily fluid balance can be determined with ample sensitivity using a combination of any two common assessment measures. Hypohydration increases heat storage by reducing sweating rate and skin blood flow responses for a given core temperature. Aerobic exercise tasks can be adversely affected if hypohydration exceeds about 2% of normal body mass, with the potential effect greater in warm environments. Hyperhydration provides no thermoregulatory or exercise performance advantages over euhydration in the heat. Excessive consumption of hypotonic fluid over many hours can lead to hyponatremia. Marked electrolyte losses can accelerate the dilution and exacerbate the problem. Hyponatremia can be avoided by proper attention to diet and fluid needs.

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